Detection and Characterization of the Photospheric and Coronal Magnetic Fields of Sunspot Groups: Implications for Flare Forecasting

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14. ABSTRACT
The effort included three science goals (SG) along with the development of the corresponding software. Specifically, the science goals were as follows: SG1 Characterizing the surface magnetic structure of active regions (ARs); SG2 Characterizing the coronal topology of ARs, and SG3 Characterizing the time dependent behavior of AR magnetic and coronal properties.

Most of the targeted scientific goals were achieved, and software has been developed to automatically track ARs and to study the evolution of surface magnetic structures (including the detection of complex delta spots). The software is successfully tested with two years (20112012) data from NASA's Solar Dynamics Observatory satellite. The algorithm automatically selects separate regions of a given AR (such as umbrae, penumbrae and quiet sun) and calculates different physical properties, such as: i) line-of-sight (LOS) magnetic flux of the entire AR; ii) LOS magnetic flux, area, and mean LOS magnetic field of the umbrae and penumbrae; iii) if a delta spot is found, the magnetic flux of delta forming spots in the AR; iv) strength and orientation of flows in the vicinity of the AR. This software is being tested in Space Weather Division of UK Met office, and will be implemented there. This was also used to analyze a large archival dataset to study the evolution of ARs and the connection to solar flares.

15. SUBJECT TERMS

EOARD, solar flares, sunspots, solar active region

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Project Final Report - May 2015

Detection and Characterization of the Photospheric and Coronal Magnetic Fields of Sunspot Groups: Implications for Flare Forecasting

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1. Summary of Project

The project proposal included three science goals (SG) along with the development of the corresponding software. Specifically, the science goals were as follows: SG1 - Characterizing the surface magnetic structure of active regions (ARs); SG2 - Characterizing the coronal topology of ARs, and SG3 - Characterizing the time-dependent behavior of AR magnetic and coronal properties. Most of the targeted scientific goals were achieved, and a software has been developed to automatically track ARs and to study the evolution of surface magnetic structures (including the detection of complex delta spots). The software is successfully tested with two years (2011-2012) data from NASA's Solar Dynamics Observatory satellite. The algorithm automatically selects separate regions of a given AR (such as umbrae, penumbrae and quiet sun) and calculates different physical properties, such as: i) line-of-sight (LOS) magnetic flux of the entire AR; ii) LOS magnetic flux, area, and mean LOS magnetic field of the umbrae and penumbrae; iii) if a delta spot is found, the magnetic flux of delta-forming spots in the AR; iv) strength and orientation of flows in the vicinity of the AR. This software is being tested in Space Weather Division of UK Met office, and will be implemented there. This was also used to analyse a large archival dataset to study the evolution of ARs and the connection to solar flares.

2. Techniques & Data used.

For this project data was used primarily from two instruments, HMI and AIA onboard SDO satellite. This data was accessed automatically in near real time and all the ARs were tracked for different properties. The data from AIA was used to study coronal temperature. To study some ARs in details the data was also obtained using CRISP at 1m-Swedish Solar Telescope.

The software was developed in IDL and tested successfully in comparison with NOAA - SRS data.

3. Results

A. Tracking of ARs and it's properties

We have characterized the magnetic configuration of sunspot groups using various
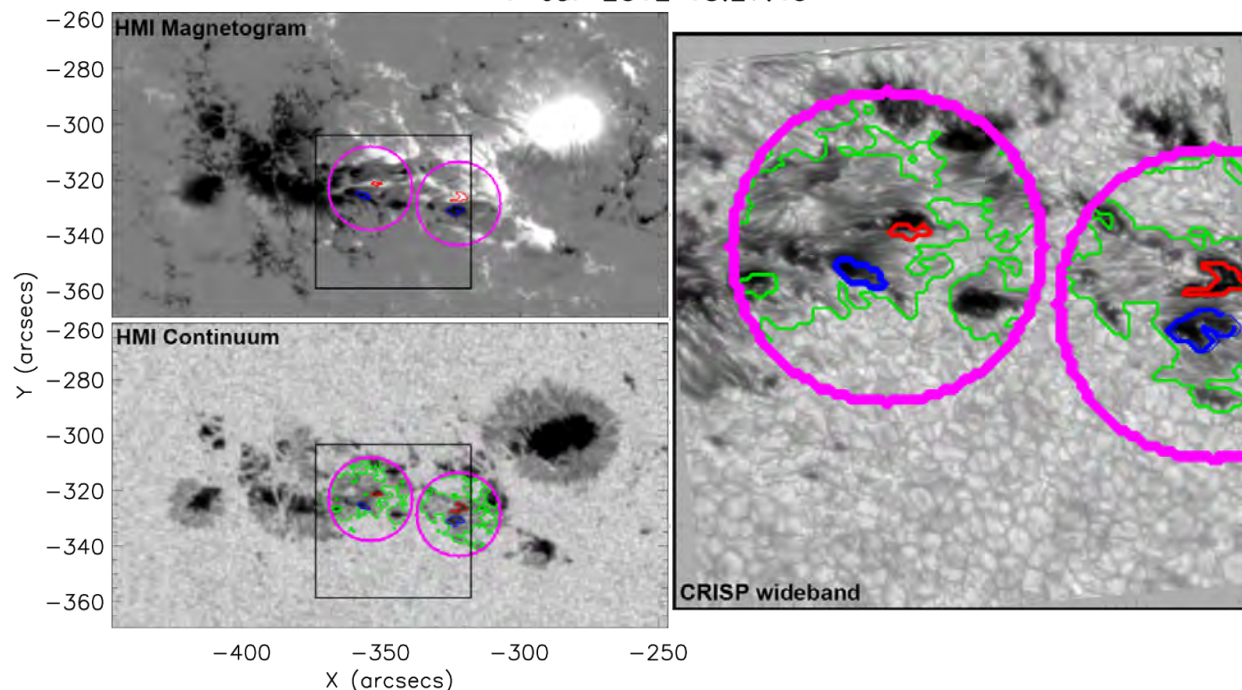

Figure 1. The delta spots detected automatically using SMART-DF code (shown in circles) using HMI data (left side). The same region observed in high resolution using 1m-Swedish Solar Telescope (right side). The red (blue) contours mark the positive (negative) polarity umbrae and green contour mark the penumbra border.

techniques. As a part of this goal, we have successfully developed a software package that monitors the evolution of all ARs on the solar disk. Each AR is detected in near-realtime using the Solar Monitor Active Region Tracker (SMART; Higgins et al., 2011). The SMART algorithm has been extended to use simultaneous measurements of continuum intensity and LOS magnetic field to segment ARs into umbrae, penumbrae and plage. Data from the HMI instrument onboard NASA's Solar Dynamics Observatory satellite is used for this purpose. The software developed here detects the formation of delta spots in an AR, using the standard delta spot definition of as given by NOAA: i) the distance between opposite polarity umbrae should be less than 2 degrees on the solar disk; ii) both umbrae should be surrounded by a common penumbra.

The software also estimates the horizontal plasma-flow in and around an AR by tracking both magnetic as well as intensity features. The program allows the user to define the size of the features to be tracked. Local correlation tracking (LCT) algorithm is used to estimate the velocity. Such horizontal velocity measurements in near-realtime will be used to study the evolution of magnetic feature in ARs. An example of horizontal velocity measurement is shown in Figure 1. Note that there is a strong velocity in the delta forming region. The

software is being tested in Space Weather division of UK Met Office. One example output from the code is shown in Figure 1.
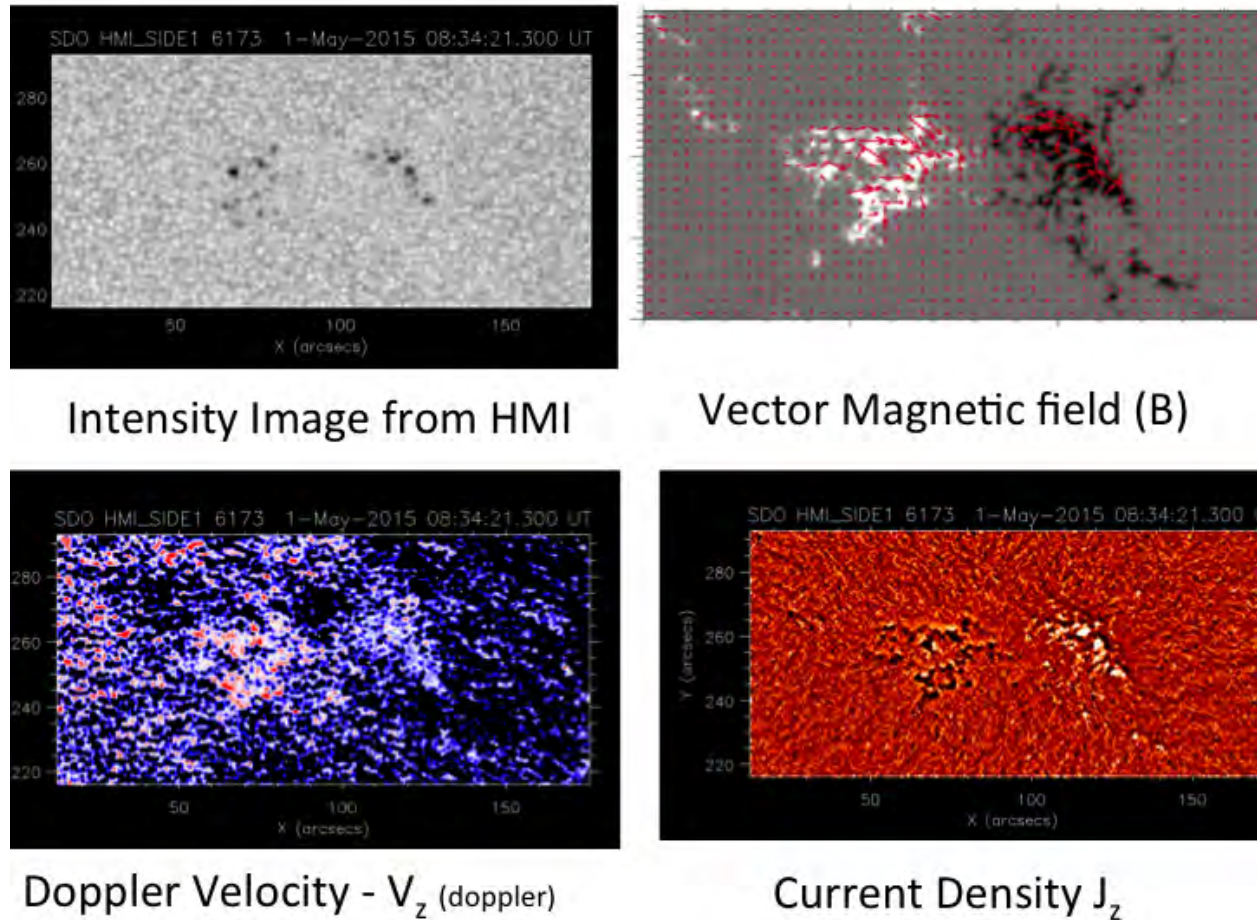

Figure 2. An Active Region (NOAA 12336) automatically analysed using the HARP-AR Tracker software.

Another software to automatically access and analyse 3-D vector magnetic field data from HMI/SDO Satellite is also developed. This data is used to calculate 3-D vector magnetic topology, and other parameters like Current density, Helicity, twist, in near-real time. This was used to study the relation between AR evolution at lower atmosphere and flares. Example images are shown in Figure 2.

B. AR studies using high resolution data.

To get a better idea about structure and dynamics of photospheric magnetic field coupling with a Solar flare in chromosphere and corona, we studied two cases using very high resolution multi wavelength data, observed with 1-m swedish solar telescope (SST). Also simultaneous data from HMI and AIA onboard SDO satellite was used for this study. The

software tools developed as a part of this project was used to analyse the data. The results show very strong shear flow along the flare ribbon and the strong shear flow between two opposite polarity pores leading to a
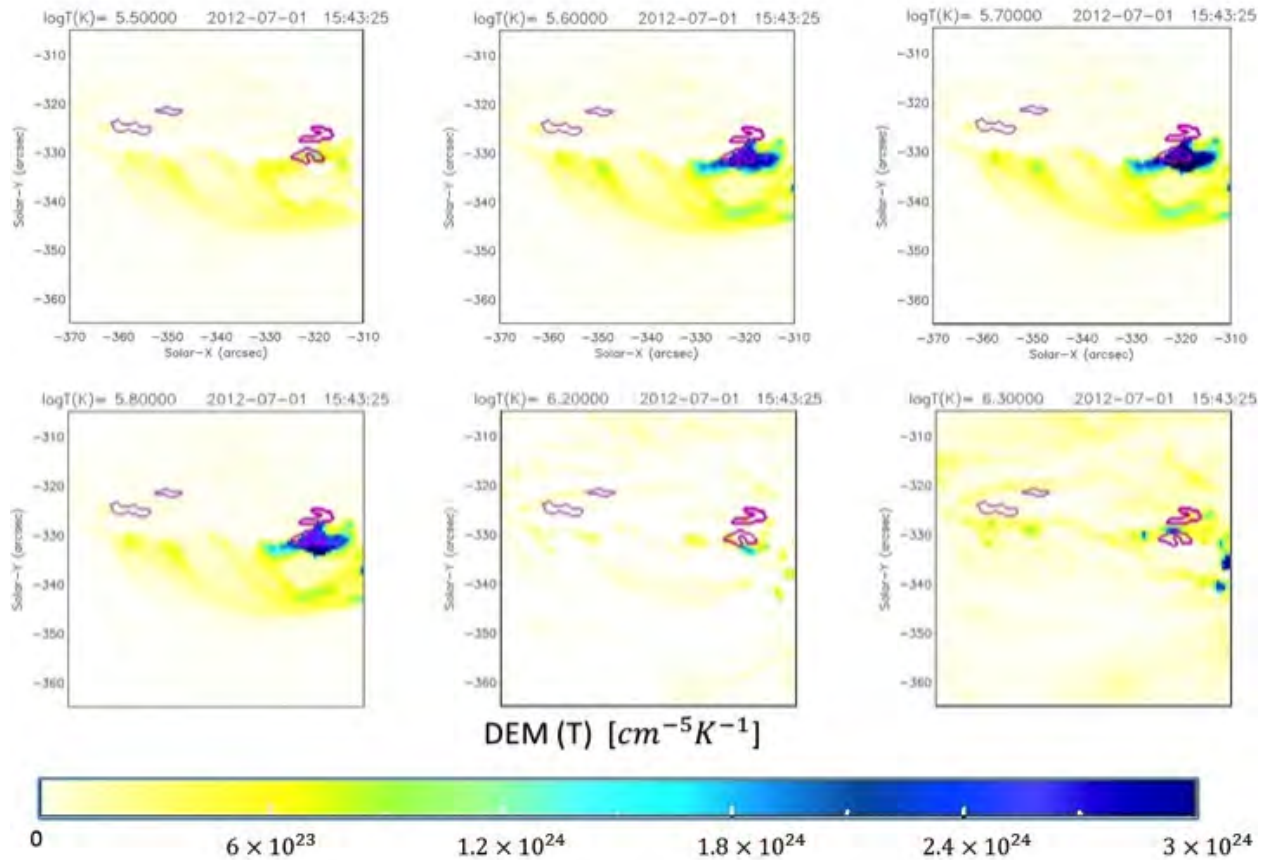

Figure 3. DEM at in different temperature range in a flaring region (NOAA AR 11515) at the beginning of a flare. The contours mark the delta spots. Note that the delta region shows stron DEM at certain temperature, compared to the loops.

solar flare. The pre-flare and post-flare conditions at higher atmospheres like Chromosphere and
corona were also studied. One example snapshot of high resolution observation is shown in Figure 1. These results are very significant and will be soon communicated to a high impact journal.

C. Differential Emission Measure from Corona

The proposed plan was to measure Coronal intensity and loop tracing to study the topology above active regions. Instead of simply measuring the intensity, a better physical parameter to measure is differential emission measure (DEM) at different temperatures. DEM is calculated

using the method given by Hannah & Kontar, 2012. The DEM estimation code is integrated with earlier developed AR-tracking code to simultaneously measure DEM at corona using AIA data from SDO. As the AR evolve and delta-spot is formed, the variation in DEM at different temperatures of corona will be studied using this software. It was observed in multiple cases that as the delta-like spots are formed it show and increased DEM at corona. One example is shown in Figure 3. A large scale statistical study on DEMs just before flare was conducted. The results will be communicated to a high impact journal.

3. **Software Tools Developed.**

Two software tools, SMART Delta findr (SMART-DF) and HARP- Active region Tracker was developed as a part of this project. The SMART-DF is also tested by Space Weather division of UK Met office, and will be implemented in their flare forecast system. HARP-Active region tracker uses HARP data patches and estimates many other parameters like vector magnetic field, current density and helicity of Active regions. Both the tools will also be integrated to SolarMonitor, and will be made available to the public.

4. **Dissemination of Results.**

The results obtained at different stages of this project were presented in two international conferences and one international workshop. Also three papers to publish in high impact international journals are being prepared and communicated, out of which one paper is already communicated to Solar Physics, and is under review process.

The details of the algorithm of the software and it's successful verification using archival NOAA data was presented at 7th Solar information processing workshop during 18-21 August 2014 held at La Roche en-Ardenne, Belgium. This work was also communicated to a prominent journal (Sreejith et al., 2015, *Solar Physics*, under review). This paper is attached here with this report.

Study of delta-spots in an AR and it's dynamics during a solar flare using high resolution data was presented at the 14th European Solar Physics Meeting (ESPM) during 8-12 Sept 2014 held at Dublin, Ireland. This paper was selected one of the best in the session, for a press release of the results. This work is also under preparation as a paper and will be communicated to a high impact international journal soon (Sreejith et al., 2015, under preparation).

Use of the software developed during this study to detect magnetic configurations like delta-spot much before NOAA in many cases and it's use to forecast flare was studied for mant cases. This result along with others were also presented at an international conference on Coupling and Dynamics of the Solar Atmosphere held during 10-14 November 2014 at Pune, India. These results are also being prepared as a journal and will be communicated to a high impact journal soon.